Beam Physics II

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DoE Review
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Fermilab

Talk outline

1. Status and plans
2. Optics
    a. Coupling
    b. Optics correction at Low Beta
3. Instabilities
4. Model of the luminosity evolution

Conclusions

1. Status and plans

- **Problems solved after previous review**
  - ^ impedance has been reduced and beam stability improved
  - Injection and flat top optics has been corrected
  - Coupling due to skew field in dipoles has been reduced
  - IP move in CDF
- **Problems to be solved within next half year**
  - Correction of optics and helix at Low Beta
  - Introducing octupoles in routine operations
    - Further improvements for transverse stability
    - Differential chromaticity
  - Matching vertical dispersion in P1 line
    - Four quads to be rolled
- **Outstanding problems**
  - Beams beam effects
    - Increase of helical beam separation
    - Beam-beam compensation
    - Beam-beam simulations and studies
  - Nonlinearities in Tevatron lattice and their compensation

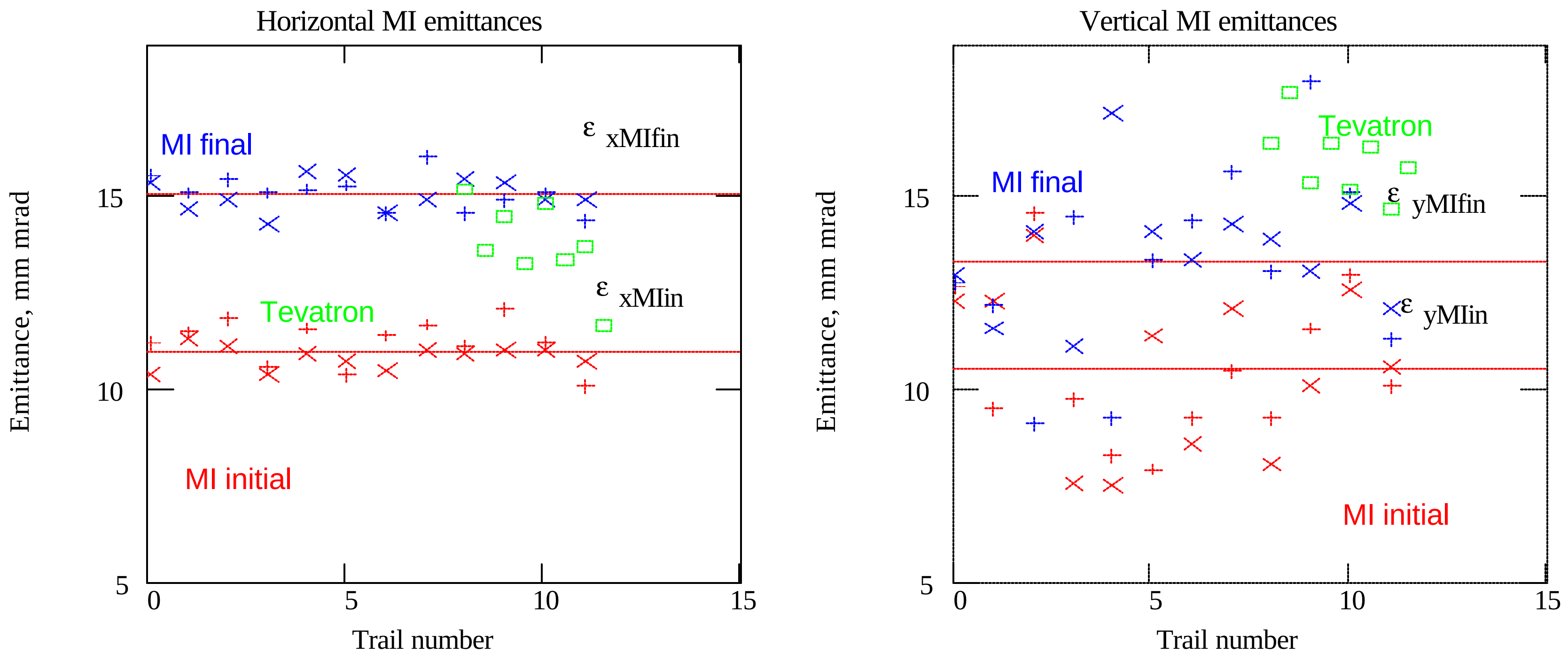
2. Tevatron Linear Optics

- Measurement and analysis
  - Differential orbits, ~10 – 15% accuracy
  - Tune shifts due to focusing change in a single quad to validate dif. orbits
  - Beta-function measurements in IPs by CDF and D0
- Status
  - Injection
    - Optics has been corrected before shutdown
      - Smaller emittance growth at beam injection, larger aperture, reduced beam-beam
    - Coupling has been improved after shutdown
      - Smaller emittance growth at the beam injection
  - Flat top (980 GeV after acceleration but before the squeeze)
    - There is no significant discrepancies with design intent
  - Low Beta (HEP)
    - Significant optics mismatch needs to be corrected
    - Non-zero crossing angle due to optics errors and inaccuracies in calibration of HV separators

Optics correction at injection performed before shutdown

Measurements of P1 and A1 lines performed in 2002 could not explain the origin of emittance growth in the round trip emittance measurements

- The measurements ruled out that the observed round trip emittance growth ~40% can be related to
  - Injection errors and/or
  - Optics distortions in MI, Tevatron and transfer lines
- Tevatron optics correction performed before shutdown (Aug. 2003) made barely visible improvement for transfers
- Coupling was the only mechanism not ruled by the optics measurements
- Reconstruction of Tevatron optics at injection (Aug. 2003) proved that
  - Coupling should bring the emittance growth of about 15% per transfer
  - Coupling cannot be compensated by existing skew-quad circuits
- The model also proved that correction of coupling for a fraction of dipoles should bring a decrease of emittance growth from ~15% to 5% per transfer
- The model shows that the skew-quad terms are not uniformly distributed through the ring and most probably A1 in dipoles are not the only source of the coupling



Measured round trip emittances after optics correction

Table. Measured and computed* round trip emittance growth

	Uncorrected Tevatron optics		Corrected Tevatron optics	
	Measured	**Computed**	**Measured**	**Computed**
$\delta\varepsilon_x$, mm mrad	**4.22±0.21**	**2.54**	**4.07±0.12**	**3.08**
$\delta\varepsilon_y$, mm mrad	**1.58±1.47**	**3.40**	**2.83±0.61**	**2.98**
$(\delta\varepsilon_x+\delta\varepsilon_y)/2$, mm mrad	**2.9**	**2.97**	**3.45**	**3.03**

* Computations were carried out for equal horiz. and vert. emittances of 11 mm mrad.

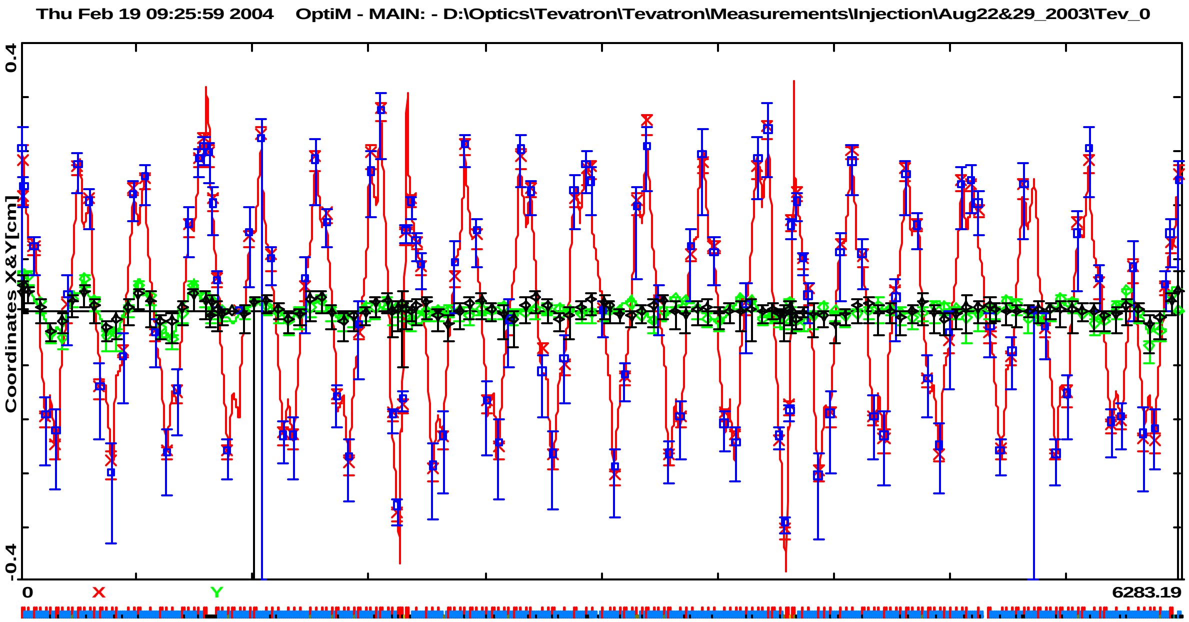
Coupling in Tevatron

A1 for 106 of 774 SC dipoles has been corrected at shutdown

- Preliminary conclusions
  - Injection optics
    - Skew quad currents were reduced as expected
    - Peak values of vertical dispersion and cross plane response for differential orbits are reduced insignificantly but
    - Emittance growth due to coupling computed from the dif. orbit measurements is reduced as it was expected
    - Shot data also show expected improvement in the emit. growth
    - Direct verification with round trip emit. measurements has been delayed by lack of study time and is expected to be performed soon
  - Low beta optics
    - A1 correction allowed to decrease skew-quad currents without increase of tune split or cross plane response in dif. orbits
    - While coupling is still a concern we are not aware about any harmful effects on Tevatron operation

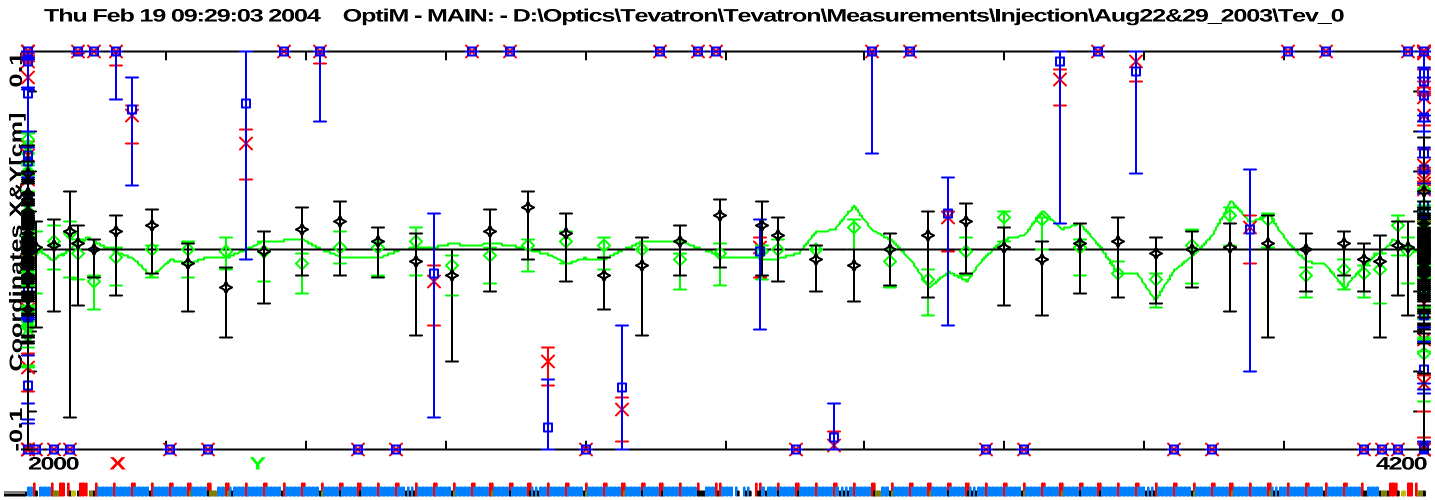
Coupling in Tevatron (continue)

Coupling and its correction at injection



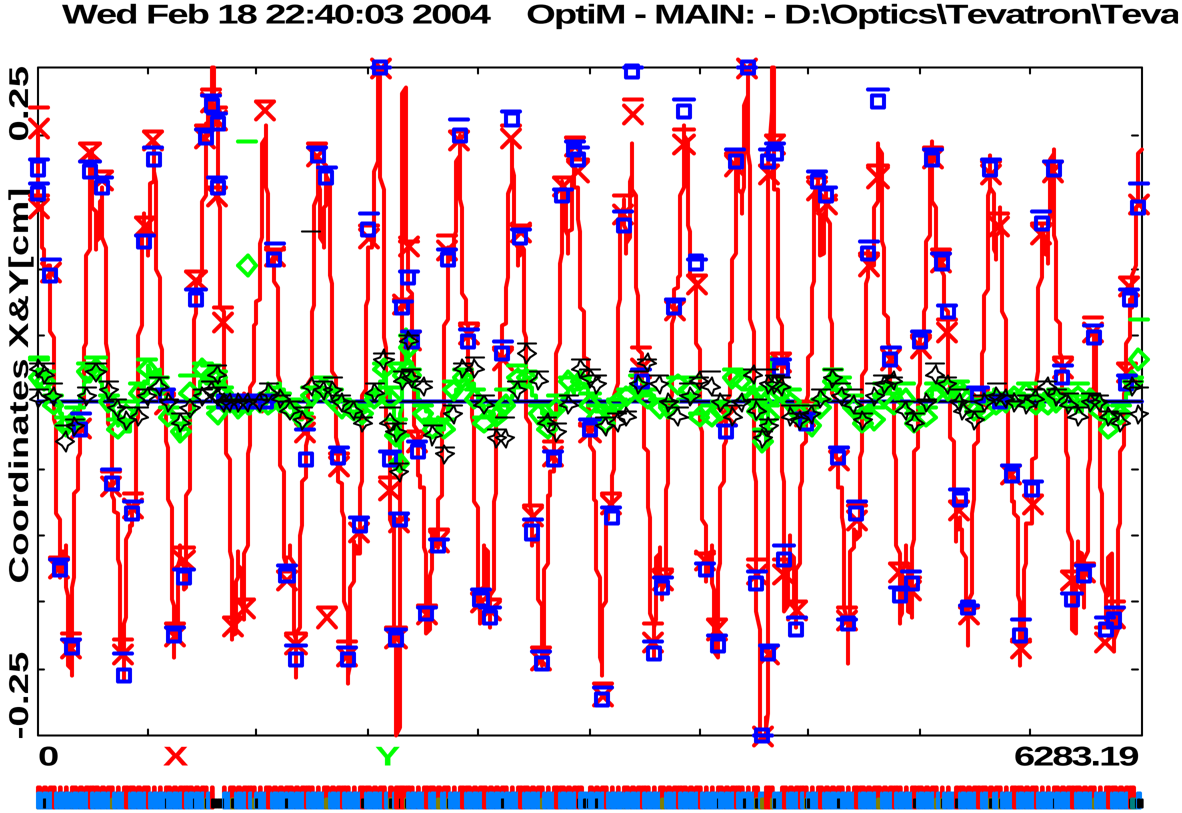
Name	Current before shutdown, A	Current after shutdown, A
T:SQ	-2.85	-2.64
T:SQA0	4.35	4.18
T:SQA4	-5.17	0
T:SQB1	0.56	0
T:SQD0	0	0
T:SQE0	1.48	0

Differential orbits for horizontal single cor. kick at injection: Red and Green – before shutdown, blue and black after shutdown. Scales are blown up at the bottom picture



Coupling in Tevatron (continue)

Coupling and its correction at low beta

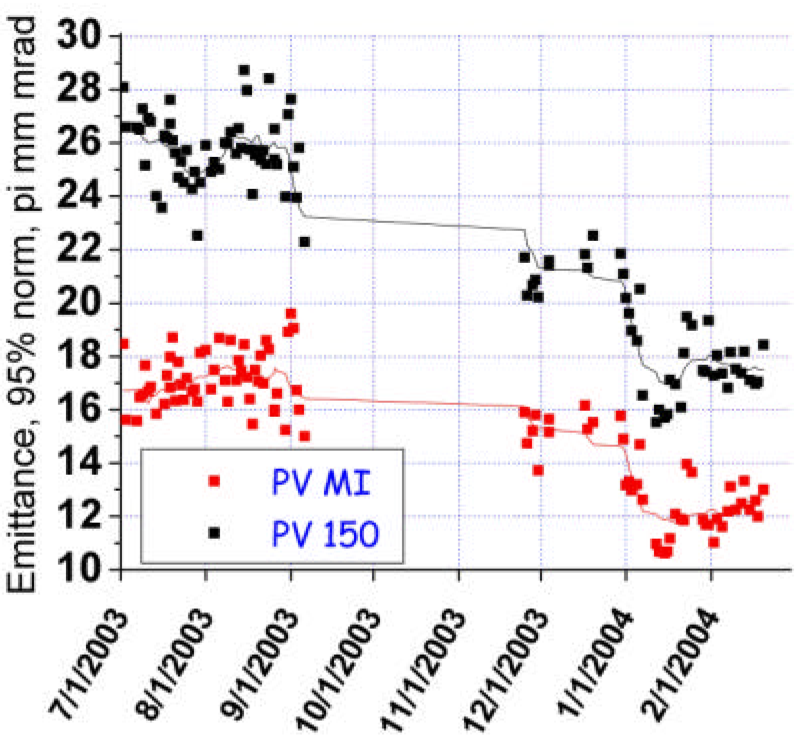


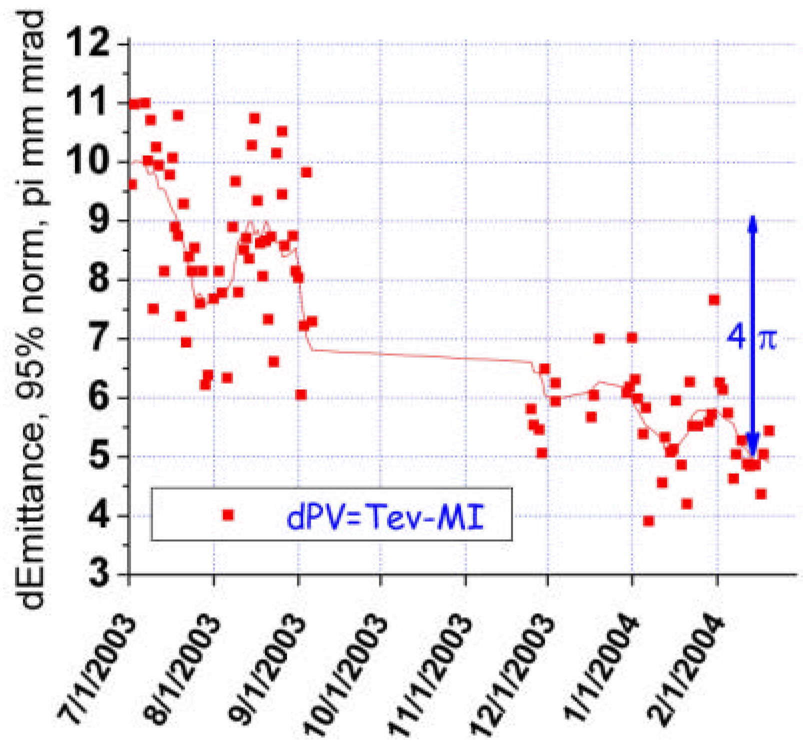
Name	Current before shutdown, A	Current after shutdown, A
T:SQ	-26.99	-25.67
T:SQA0	15.87	4.96
T:SQA4	-21.85	4.50
T:SQB1	0.93	4.50
T:SQD0	4.73	0
T:SQE0	0	0

Differential orbits for horizontal single cor. kick at low beta: Red and Green – before shutdown, blue and black after shutdown

- Plans for further improvements
  - BPM upgrade will yield much better measurement accuracy
  - Software improvements will yield more accurate and trustable model
    - first tests are presently carried out

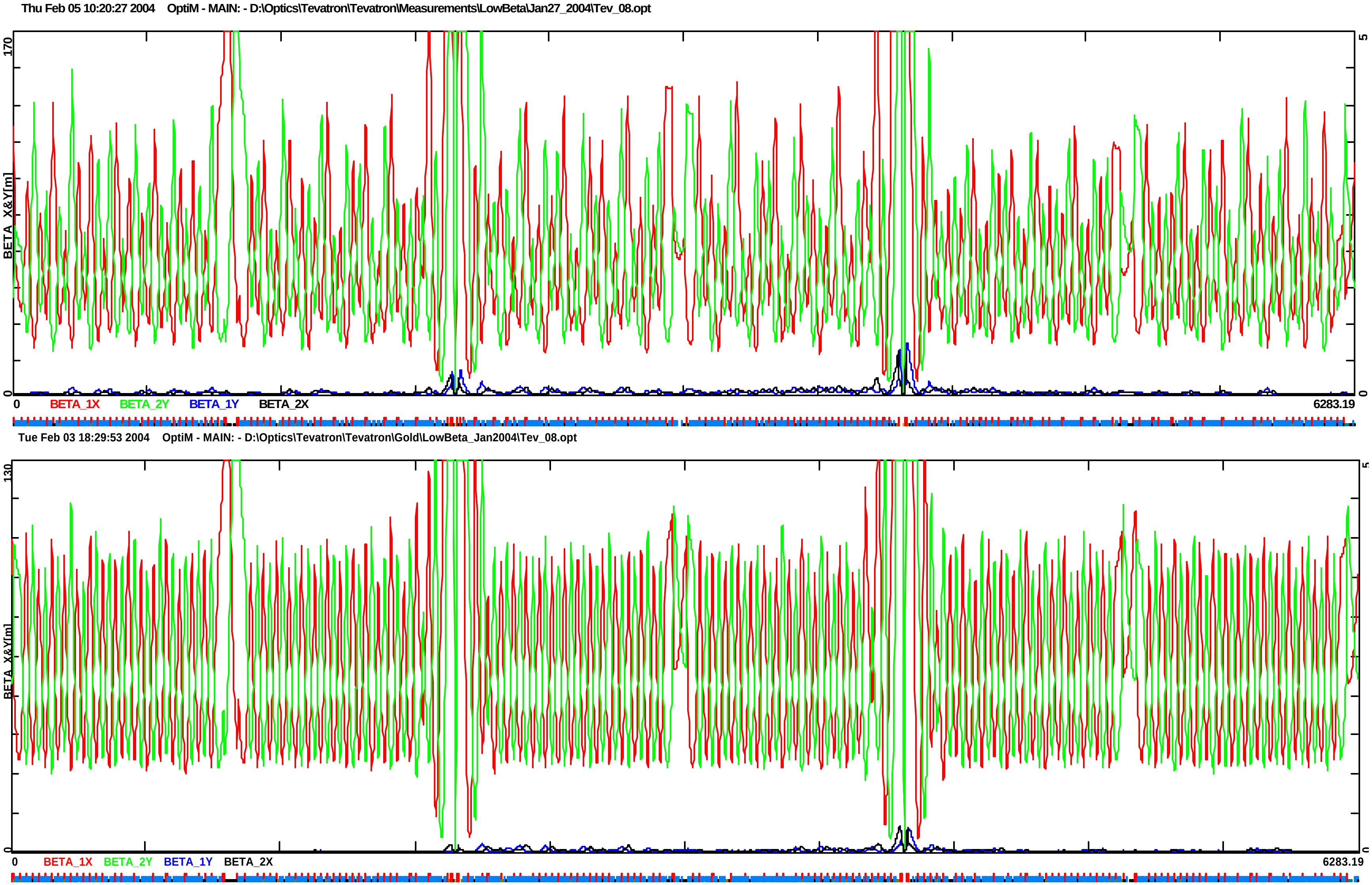
Coupling in Tevatron (continue)





- Vert. emit. in MI (150 GeV) has been improved by ~6 mm mrad
- Emittance growth at the MI-to-Tevatron transfers was reduced by ~4 mm mrad as it was expected due to coupling improvements
- Relative calibration of MI and Tevatron emittance monitors (Aug.2003, see picture at page 5) showed ~5 mm mrad discrepancy.
  - Thus the present vert. emittance growth of ~5 mm mrad is most probably related to the instrumentation miscalibration

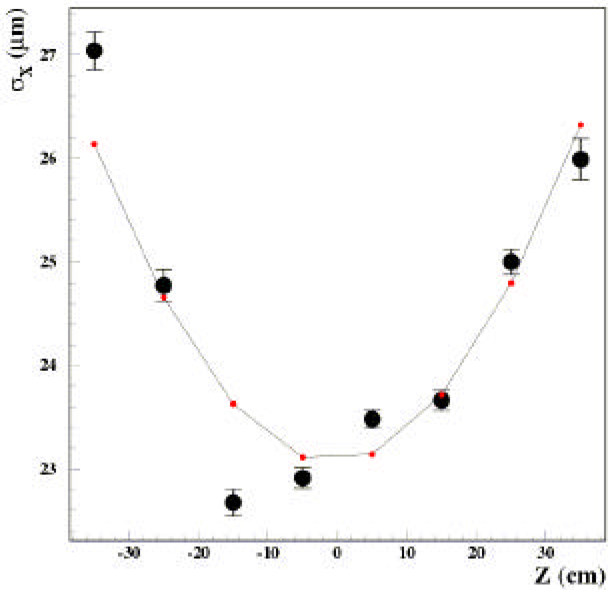
Optics Correction at Low beta

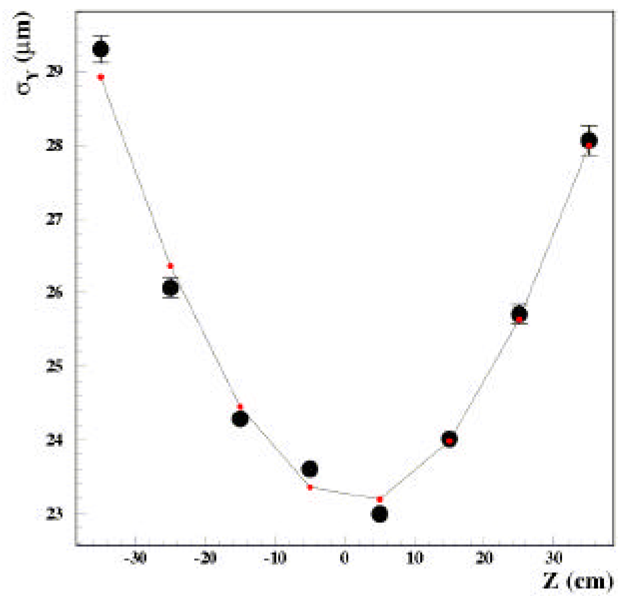


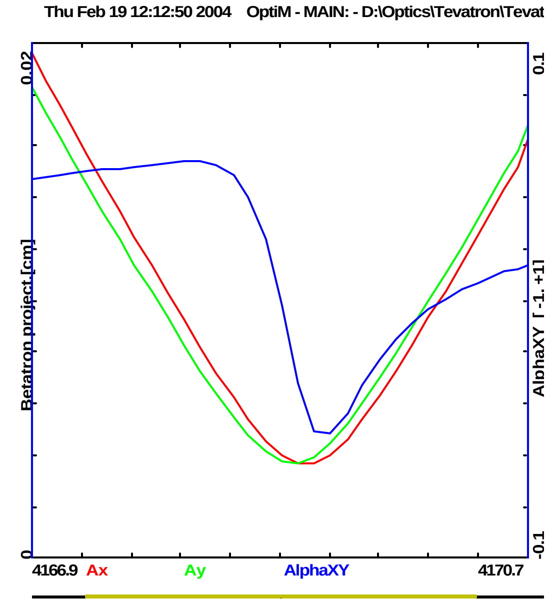
Beta functions for present Tevatron optics (top) and after optics correction

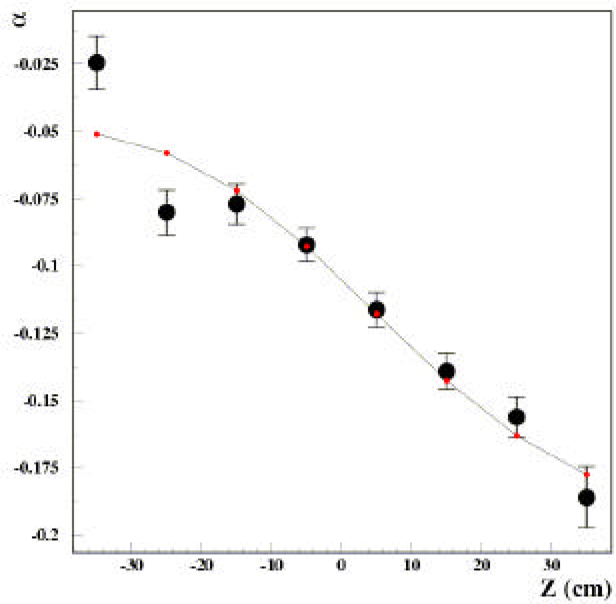
- There is considerable optics mismatch for Low Beta Tevatron optics

Measurements of luminous region parameters in D0 for store 3172









Horizontal and vertical sizes of the luminous region near D0 IP and parameter α describing ellipse tilt

$$\alpha = \langle xy \rangle / \mathrm{sqrt}\left(\langle x^2 \rangle \langle y^2 \rangle\right)$$

- Good measurements to find the beam waists
  - It can be affected if optics at proton and pbar helix are different
- Good indication of how well is optics tuned
- There is considerable coupling in IPs

Optics Correction at Low beta (continue)

Validation of the model

Comparison of tune shifts measured directly with the tune shifts computed from differential orbit measurements

	ΔI [A]	δQx (meas)	δQy (meas)	Ratio Meas/Model
E17(X)	30	0.0085	0.0034	
E19(X)	20	0.0081	0.0012	
E47(Y)	20	0.002	0.0071	
F33(Y)	20	0.0015	0.0091	
	ΔI [A]	δQx (model)	δQy (model)	
E17(X)	30	0.010205	0.003839	**0.83**
E19(X)	20	0.008331	0.001858	**0.97**
E47(Y)	20	0.001842	0.008077	**0.88**
F33(Y)	20	0.001633	0.009373	**0.97**

Positions of the beam waists in IP computed from the model and measured by CDF and D0 (store 3123, 2 Jan. 2004)

	CDF		D0	
	Zx[cm]	Zy[cm]	Zx[cm]	Zy[cm]
Model	22	-10	9	19
Direct meas.	12.1 ±1.2	-9.7 ±1.4	1.9 ±0.8	1.51 ±0.3

Beta-functions at the waist in IP computed from the model and measured directly by CDF and D0

	CDF		D0	
	βx[cm]	βy[cm]	βx[cm]	βy[cm]
Model	46	41	38	37
Direct meas.	45 – 60			

Optics Correction at Low beta (continue)

To correct the optics the following quad changes are suggested:

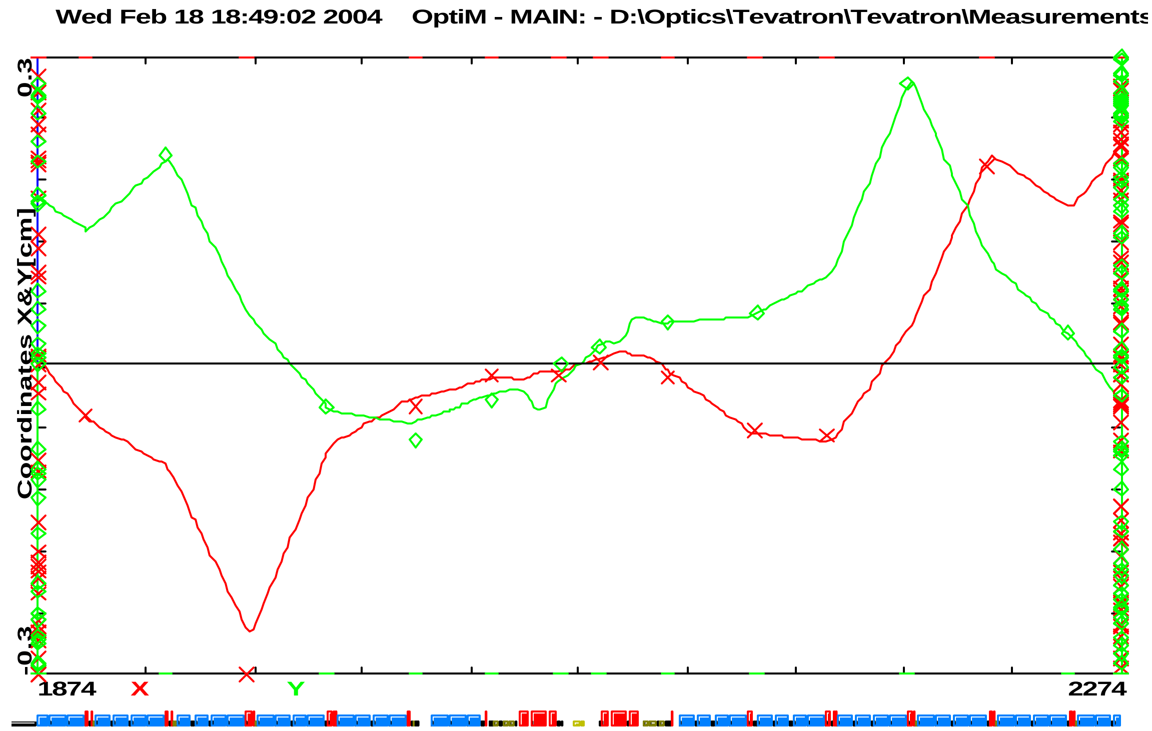
Name	Assignment	Present value, A	Increment	New value, A
AQ9	B0, X	555.560	-250 A	305.560
AQ7	B0, X	607.437	-70 A	537.437
BQ7	B0, Y	680.084	-10 A	670.084
BQ9	B0, Y	479.718	-50 A	429.718
CQ9	D0, X	555.560	-30 A	525.560
CQ7	D0, X	607.437	20 A	627.437
DQ7	D0, Y	680.084	0	680.084
DQ9	D0, Y	479.718	-100 A	379.718
B0Q3	B0, IP pos	4666.29	-10 A	4656.29
D0Q3	D0, IP pos	4636.99	-8 A	4628.99
B0QT3		3.8696	-3.8696	0
ΔQ_h	Tune corr.	-	0.034	-
ΔQ_v	Tune corr.	-	0.033	-

Optics Correction at Low beta (continue)

- Model accuracy of $\Delta\beta/\beta \sim (10 - 15)\%$ is factor of 3 better than optics mismatches $\Delta\beta/\beta \sim (30 - 50)\%$ but is not sufficiently good
- Therefore optics correction has to be validated by
  - tune changes due to quadrupole focusing changes
  - and by beam waist measurements in IPs
- Procedure for correction
  - First, fix beta-functions in arcs
  - Second, use α – bumps to correct waist positions
- Both optics reconstruction from the differential optics measurements and from direct measurements in IPs show beta-functions in IPs larger than the design
  - Correcting the problem should yield ~10-15% increase in peak luminosity

Helix Correction at Low beta

- There are a number of discrepancies making helices different from the design intent
  - Optics distortions and coupling
  - Finite accuracy of HV separators and their rolls
- Beam positions coincide well in IPs
- Getting angles correct is more cumbersome
- Reconstruction of helical orbits showed not negligible crossing angles in IPs

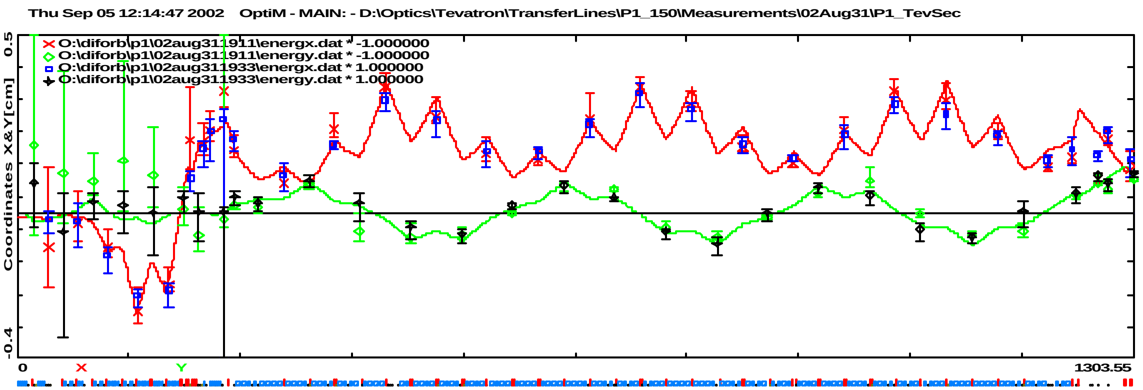


Reconstruction of helical orbits in vicinity of CDF from BPM data taken at Feb.5 2004,
Half-crossing angles: θ_x = 7.4 μrad, θ_y = 23 μrad
That yields ~ 6% drop in luminosity

- Crossing angle correction should yield luminosity growth ~5% and reduce the beam-beam effects

Correction of vertical dispersion in P1 line (p MI to Tevatron)

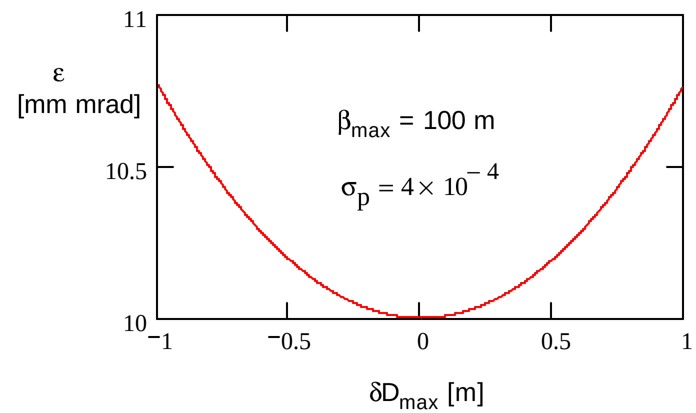
- There is considerable vertical dispersion mismatch in P1 line
  - ➢ $D_y \sim 1$ m $\Rightarrow \delta\varepsilon_v \sim 1$ mm mrad



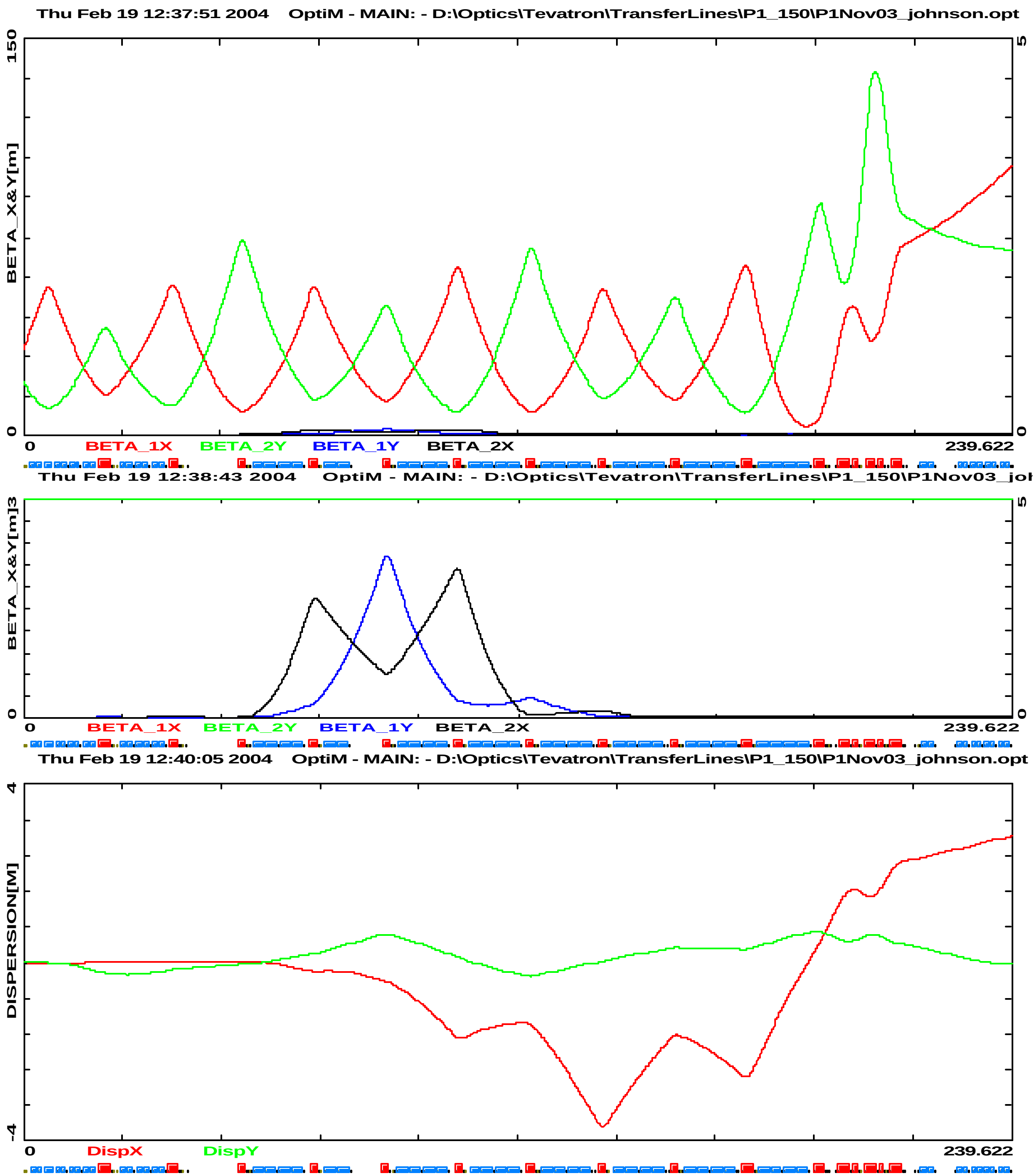
- To address the problem we plan to roll 4 quads in P1 line
  - ➢ 2 quads are used to match D and D`
  - ➢ 2 other quads compensate coupling
- Expected luminosity growth ~5%

Requirements for dispersion mismatch for MI to Tevatron transfer

$$e_2 \approx e_1\left(1 + \frac{(s_p dD_{max})^2}{2b_{max}}\right)$$



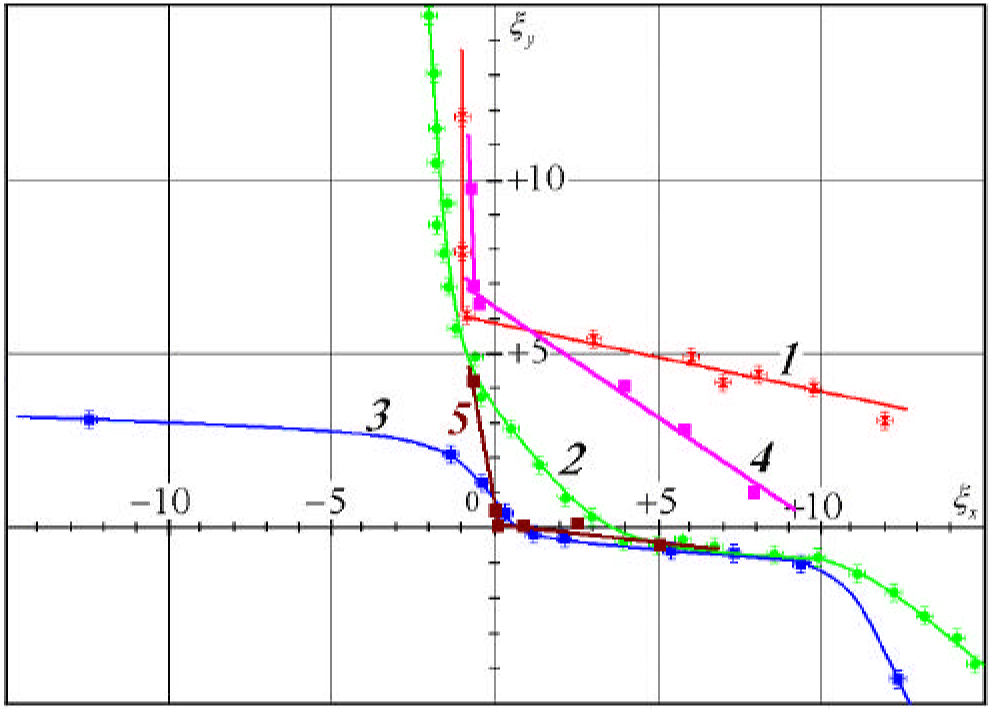
- Dispersion mismatch below about 0.5 m does not produce significant emittance growth



Required rolls of the quads:

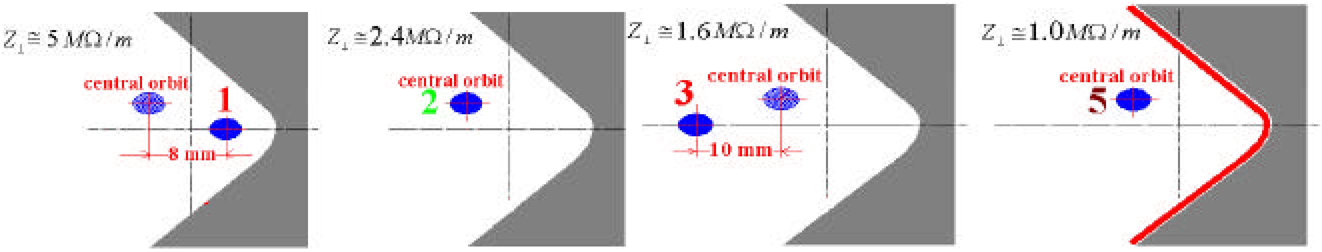
Q703	2.9 deg
Q705	0.85 deg
Q707	-3.0 deg
Q709	-0.89 deg

3. Instabilities



- *All measurements are performed with single proton bunch:*
  - *curves 1-4 - N_{ppb}=2.6*10^{11}*
  - *5-th curve: N_{ppb}=1.85*10^{11}*
- *The thresholds are determined by an increase of Schottky signal as a chromaticity is smoothly decreased.*

Proton beam positions at the notch of the F0-Lambertson magnet



1. Injection orbit **2. Central orbit** **3. Local orbit bump Dx=-10 mm** **5. Central orbit with liners**

- Shielding of F0 lambertson made beam stable for all positive chromaticities
- Introducing tune spreads with octupoles should allow as to work at zero chromaticity

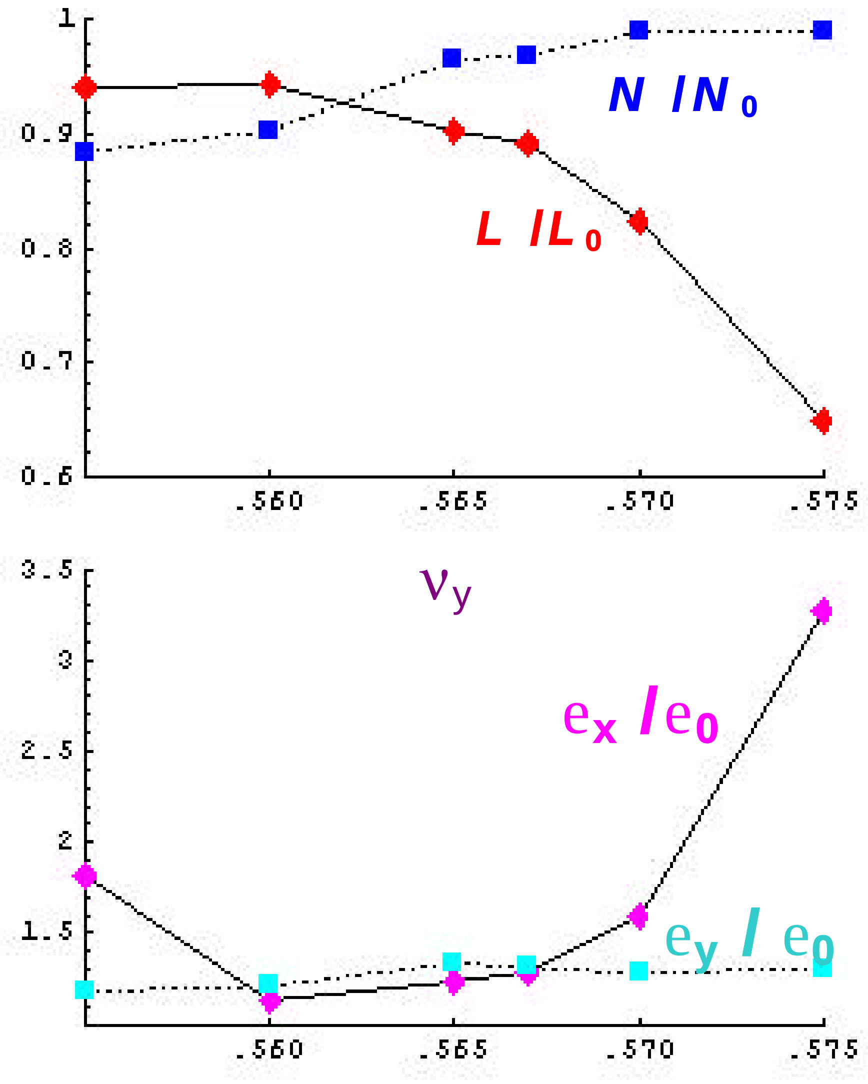
4. Model of the luminosity evolution

- The model presented at the previous reviews included the basic diffusion mechanisms but ignored the beam-beam effects
- To improve the model we are carrying out the following actions
  - Theory
    - Simulation of the beam-beam effects in the presence of external noise
  - Experimental studies require a detailed knowledge of evolution of the transverse and longitudinal distribution functions and the tunes
    - That implies improvements in diagnostics
      - Tunes for each bunch are recorded to SDA. Further improvements in tune measurements are required
      - Measurements of longitudinal distribution function during a store is under development
        - Raw SBD data are in SDA
        - On-line reconstruction of longitudinal distribution will follow

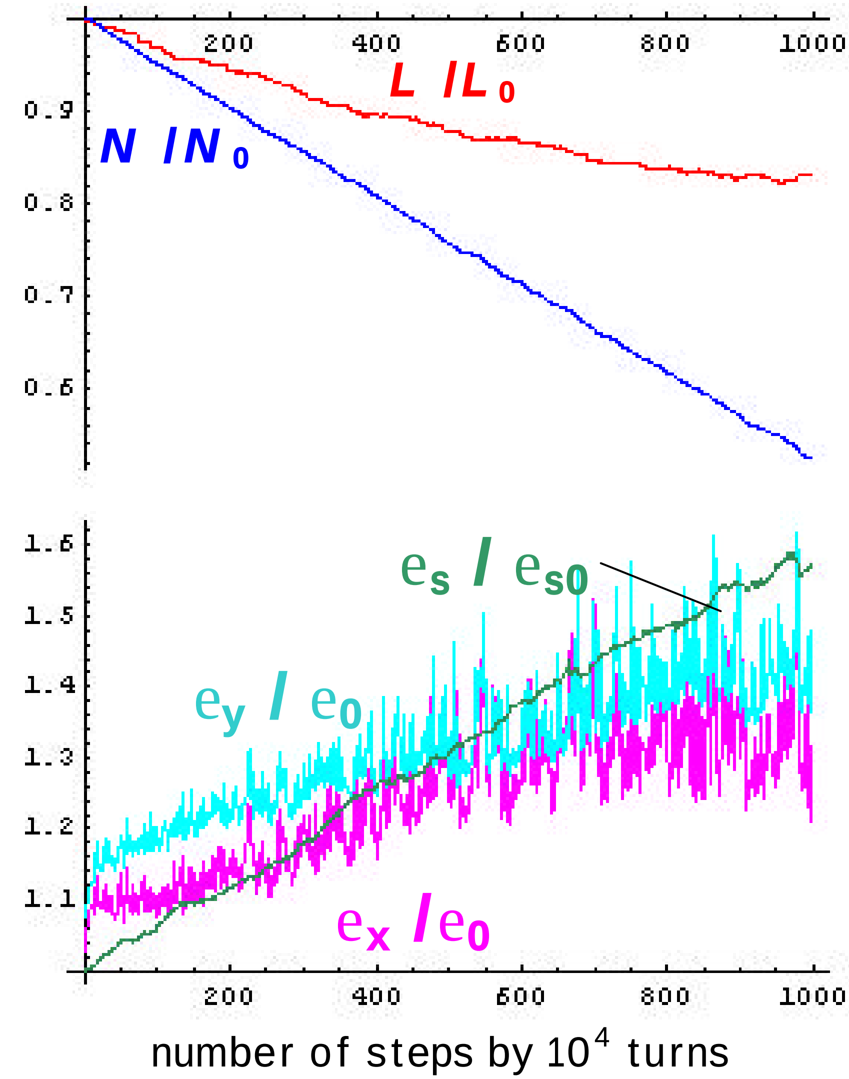
Beam-beam simulations with LifeTrack

- The model includes
  - Weak-strong interaction
  - Linear lattice with built-in chromatisities of tunes and beta-functions.
    - Beta-functions chromaticities are excited by the final focus quadrupoles, $(b/p)\cdot(db/dp) \approx 500$.
    - X-Y coupling measured in Tevatron is included
  - Beam-beam kicks
    - Kicks are computed for a bunch with gaussian distribution. The bunch rotations due to coupling are taken into account
    - Single kick at parasitic collisions
    - Multiple kicks in main IPs to take into account the phase averaging
  - Synusoidal RF voltage
  - Diffusion is simulated by random kicks in all 3 degrees of freedom
- We are testing software to understand its applicability to Tevatron
  - $\sim 10^7$ turns and 10,000 particles are required for reliable simulations

Beam-beam simulations with LifeTrack (continue)



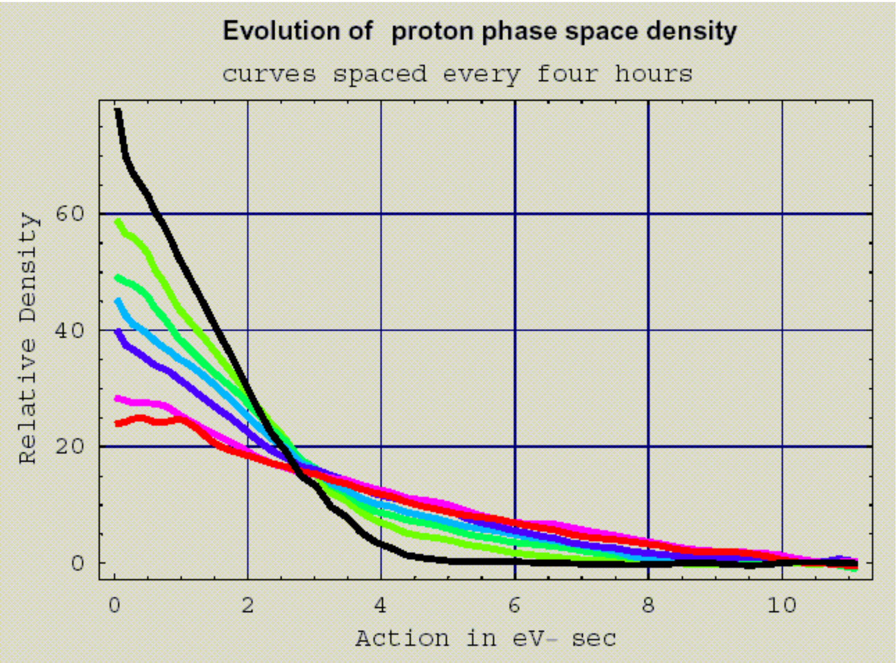
Tune scan along the main diagonal (lattice tunes n_x =n_y +.01), 2·10^6 turns

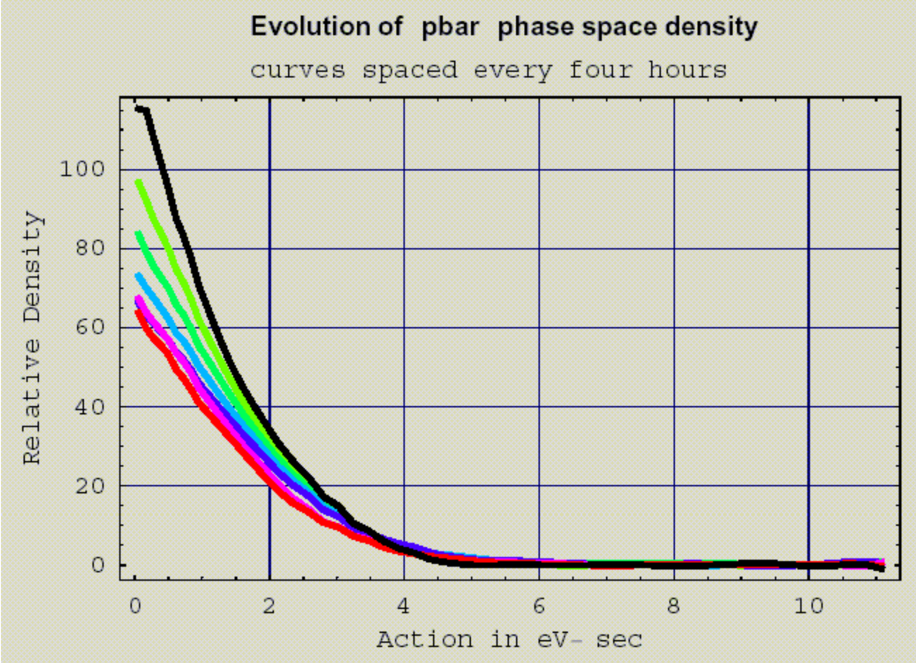


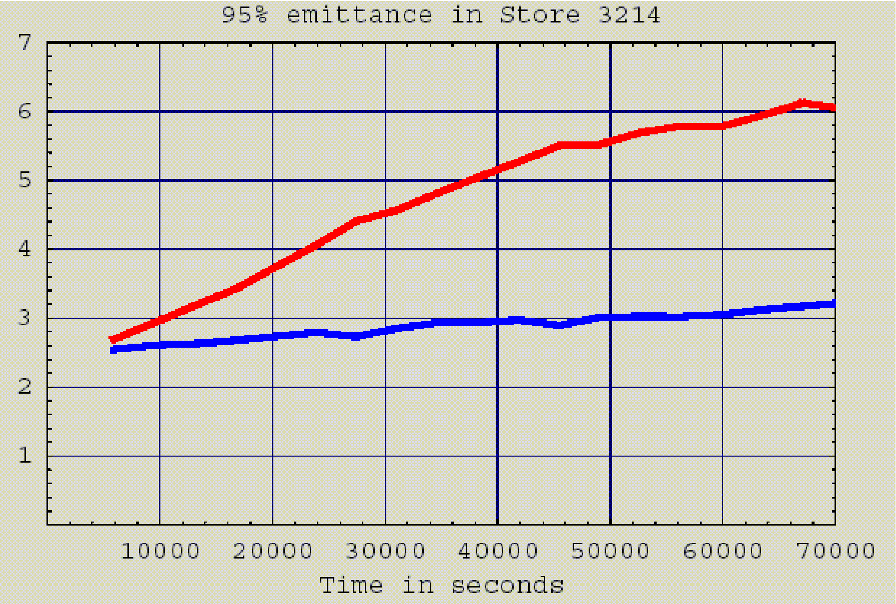
Tracking at WP n_x =.57, n_y =.56 for 10^7 turns

Alexahin, Valishev, Shatilov

Dynamics of beam distribution in the longitudinal phase space







- Distribution functions are computed from signals of the resistive wall monitor (SBD)
- Entire bucket of 4.2 eV·s is filled at injection
- There is no long. emittance growth during acceleration
- Entire proton bucket of 10.7 eV·s is filled at the end of store

Conclusions

- There was a number of problems corrected in Tevatron during 3 years of Run II commissioning and operation
- There is still a significant potential for further improvements which should yield growth of both peak and integrated luminosities
- Major improvements planned for near future
  - Linear optics
    - Correcting problems with Tevatron optics and helices
    - Correcting vertical dispersion in P1 line
  - Introducing octupoles into routine operations
    - Further increase of proton current
- It is feasible to achieve the peak luminosities exceeding $80 \cdot 10^{30}$ cm^{-2}s^{-1} for the present pbar stack
- Further luminosity growth will be mainly related with increase of pbar production
  - pbar intensity growth has to be supported by Tevatron.

Backup slide

Emittance growth due to coupling and optics mismatches

a) Emittance growth due to betatron and dispersion mismatch from a lattice with b_1, a_1, D_1 and D_1' to a lattice with b_2, a_2, D_2 and D_2' is

$$e' = \frac{e}{2}\left(\frac{b_1}{b_2}\left[1+a_2{}^2\right] + \frac{b_2}{b_1}\left[1+a_1{}^2\right] - 2a_1 a_2\right) +$$

$$\frac{s_p{}^2}{2}\left(b_2 (D_0' - D_1')^2 + 2a_2 (D_0' - D_1')(D_0 - D_1) + \frac{(D_0 - D_1)^2}{b_2}\left(1+a_2{}^2\right)\right)$$

$$\Rightarrow \qquad \frac{de}{e} \approx \frac{1}{2}\left(\frac{\Delta b}{b}\bigg|_{\max}\right)^2 + \frac{(s_p dD_{\max})^2}{2eb_{\max}}$$

b) Emittance growth for beam transfer from an uncoupled lattice with b_x, a_x, b_y and a_y, to a coupled lattice described by b_{1x}, a_{1x}, b_{1y}, a_{1y}, b_{2x}, a_{2x}, b_{2y} and a_{2y} with the eigen-vectors

$$e_1' = e_1 A_{11} + e_2 A_{12}$$

$$e_2' = e_1 A_{21} + e_2 A_{22}$$

$$A_{11} = \frac{1}{2}\left(\frac{b_x}{b_{1x}}\left[(1-u)^2 + a_{1x}{}^2\right] + \frac{b_{1x}}{b_x}\left[1+a_x{}^2\right] - 2a_{1x}a_x\right)$$

$$A_{12} = \frac{1}{2}\left(\frac{b_y}{b_{1y}}\left[u^2 + a_{1y}{}^2\right] + \frac{b_{1y}}{b_y}\left[1+a_y{}^2\right] - 2a_{1y}a_y\right)$$

$$A_{21} = \frac{1}{2}\left(\frac{b_x}{b_{2x}}\left[u^2 + a_{2x}{}^2\right] + \frac{b_{2x}}{b_x}\left[1+a_x{}^2\right] - 2a_{2x}a_x\right)$$

$$A_{22} = \frac{1}{2}\left(\frac{b_y}{b_{2y}}\left[(1-u)^2 + a_{2y}{}^2\right] + \frac{b_{2y}}{b_y}\left[1+a_y{}^2\right] - 2a_{2y}a_y\right)$$